EVALUATION OF DUCTILE FAILURE IN SHEET METAL FORMING USING A DAMAGE MODEL

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ABSTRACT
Continuous Damage Mechanics (CDM) may constitute an alternative to the traditional use of Forming Limit Diagrams (FLDs) to predict the onset of formability in sheet metal forming [1]. In CDM, at the constitutive level, a damage variable is introduced to model, at the macro scale, the internal material degradation due to micro-defects that occur during plastic loading. This approach is used in this work and the implementation of a continuum damage model in a commercial code is described, in order to identify ductile fracture in sheet metal forming. The model includes Lemaitre's ductile damage evolution law coupled with an orthotropic plasticity criterion and the resulting constitutive equations are implemented and assessed in the prediction of fracture initiation in sheet metal forming processes comparing the obtained numerical solutions with experimental results.

Keywords: Failure prediction, Damage model, Sheet metal forming.

1. INTRODUCTION

The use of numerical methods, such as the finite-element method, to handle large deformation plasticity has created the possibility to analyze with a relative success a forming process during its development stage, thus reducing the experimental tryout and tuning of new tools. This reduction can provide a faster and cost-effective development of high quality products, imperative in today's strong competition. Despite all accomplished progresses in numerical methods, these techniques still have limitations in predicting the development of localized necking, a result of an unsuccessful stamping process and a crucial issue in the process design stage. Moreover, the implemented numerical model must deal with the fact that the onset of necking is strongly dependent on the strain paths imposed to the parts. Some models include *a posteriori* fracture indicators that are not always suitable for all deformation paths. In many cases those criteria do not take into account the facts that the damage localization site may be away from the zones where the maximum equivalent plastic deformation is located or that damage evolution may be different for compression or traction stress states. The utilization of a CDM framework may be a solution for those drawbacks. Within this framework, a local damage model, based on the Lemaitre's ductile damage evolution law and fully coupled with Hill's orthotropic plasticity criterion is implemented in a commercial code [2]. To illustrate the applicability of the implemented model an experimental failure case in a sheet metal forming process is selected and the corresponding numerical simulation results are compared with the experimental ones.

2. LEMAITRE'S ELASTO-PLASTIC DAMAGE MODEL

Internal damage can be defined as the presence and evolution of cracks at the microscopic level which may lead to a complete loss of loading capability of the material – failure. Constitutive models based on CDM account for the evolution of internal degradation that may cause failure. Therefore in this work, the constitutive equations for an elasto-plasticity model described by the anisotropic Hill' 48 yield criterion coupled with Lemaitre's damage model [3] were implemented in ABAQUS/Explicit code in order to predict failure in sheet metal forming operations. The implemented model includes evolution of internal damage, isotropic hardening and anisotropic behaviour for the description of rolled plate sheets.

2.1 Hill'48 Yield Criterion

Hill's criterion [4] has been introduced as an orthotropic extension of the standard von Mises criterion in order to model the anisotropy often found in formed steel. With σ_{ij} denoting the stress tensor components on an orthonormal basis $\{e_1, e_2, e_3\}$ whose vectors coincide with the principal axes of plastic orthotropy, the yield function associated with the Hill criterion can be cast in the following form:

$$\begin{aligned}\Phi(\boldsymbol{\sigma},\bar{\sigma}) &= F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + \\ &H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{13}^2 + 2N\sigma_{12}^2 - \bar{\sigma}^2\end{aligned} \quad (1)$$

or, in terms of the array of stress components, as

$$\Phi(\boldsymbol{\sigma},\bar{\sigma}) = \boldsymbol{\sigma}^T \mathbf{M} \boldsymbol{\sigma} - \bar{\sigma}^2 \quad (2)$$

where $\bar{\sigma}$ is the relative yield stress (a non-dimensional scalar) which defines the size (state of hardening) of the yield surface in the space of stress components and **M** is the fourth-order operator of Hill as a function of coefficients F, G, H, L, M and N. These coefficients are constants which are determined by testing the material in different orientations. They are defined as:

$$\begin{aligned}&F = \frac{H}{r_{90}}; \quad G = \frac{1}{r_0 + 1}; \quad H = r_0 G; \quad L = 1.5; \\ &M = 1.5; \quad N = \frac{1}{2}\frac{(r_0 + r_{90})(2r_{45} + 1)}{r_{90}(r_0 + 1)}\end{aligned} \quad (3)$$

where r_0, r_{45} and r_{90} are the anisotropic coefficients (Lankford's r-values). Their values are the anisotropic material data given in terms of ratios of width strain to thickness strain along different directions.

2.2 Lemaitre Ductile Damage Model

The model formulated by Lemaitre [3] defines the damage variable as the neat area of a unit surface cut by a given plane corrected for the presence of existing cracks and cavities. Based on the concept of effective stress and the hypothesis of strain equivalence [3,5] and assuming homogenous distribution of micro-voids, the effective stress tensor, $\tilde{\sigma}$, can be represented as:

$$\tilde{\boldsymbol{\sigma}} = \frac{\boldsymbol{\sigma}}{1-D} \quad (4)$$

where $\boldsymbol{\sigma}$ is the stress tensor for the undamaged material. In addition, the damage variable, D, can assume values between 0 (undamaged state) and 1 (rupture). The evolution law for the internal variables can be derived from a potential of dissipation which is decomposed into plastic, ψ_p, and damage, ψ_d, components as:

$$\psi = \psi_{\mathrm{p}} + \psi_{\mathrm{d}} = \Phi + \frac{r}{(1-D)(s+1)}\left(\frac{-Y}{r}\right)^{s+1} \quad (5)$$

for a process accounting for isotropic hardening and isotropic damage, in which r and s are material and temperature dependent properties and Φ and Y are respectively, the yield function and the damage energy release rate, given by:

$$Y = \frac{-1}{2(1-D)^2}\boldsymbol{\sigma} : \left[\mathbf{D}^e\right]^{-1} : \boldsymbol{\sigma} \quad (6)$$

where E and υ denote, respectively, the Young's modulus and the Poisson's ratio of the undamaged material.
By the hypothesis of generalized normality, the plastic flow equation is obtained as

$$\dot{\varepsilon}^{\mathrm{p}} = \dot{\gamma}\frac{\partial \psi}{\partial \sigma} \quad (7)$$

and the evolution law for the internal variables as

$$\begin{aligned} \dot{\alpha} &= -\dot{\gamma}\frac{\partial \psi}{\partial q} = \dot{\gamma} \\ \dot{D} &= -\dot{\gamma}\frac{\partial \psi}{\partial Y} = \dot{\gamma}\frac{1}{1-D}\left(\frac{-Y}{r}\right)^{s} \end{aligned} \tag{8}$$

where α is the internal variable associated with isotropic hardening and $\dot{\gamma}$ is the plastic consistency parameter, which is subjected to the loading/unloading condition expressed by the complement-tarity law:

$$\dot{\gamma} \geq 0, \qquad \phi \leq 0, \qquad \dot{\gamma}\phi = 0 \tag{9}$$

2.3 Integration Algorithm

The integration algorithm for the Lemaitre's coupled elasto-plastic damage equations is a particularisation of the general implicit elastic predictor/return mapping scheme. In this case, the state update algorithm follows the steps:

a) Elastic Predictor: Given a strain increment $\Delta\boldsymbol{\varepsilon}$ and assuming that all strain is elastic, the computation of the elastic trial state is defined as :

$$\begin{aligned} \boldsymbol{\varepsilon}_{n+1}^{e\ trial} &= \boldsymbol{\varepsilon}_{n}^{e} + \Delta\boldsymbol{\varepsilon} \\ \boldsymbol{\sigma}_{n+1}^{trial} &= \omega_n \mathbf{D}^e \boldsymbol{\varepsilon}_{n+1}^{e\ trial} \end{aligned} \tag{10}$$

where $\mathbf{D}^e$ is the linear elasticity tensor and ω_n is the material integrity defined as:

$$\omega_n = 1 - D_n \tag{11}$$

If the trial state is outside the elastic domain defined by the yield function, the return mapping described bellow is applied.

b) Return Mapping Algorithm: By us-ing the linear elastic law to define $\boldsymbol{\sigma}_{n+1}$ and after a straightforward manipulation, the return mapping can be reduced to the solu-tion of two non-linear equations (by the Newton method) for the incremental plastic parameter $\Delta\gamma$ and for the material integrity ω_{n+1}:

$$\begin{cases} \boldsymbol{\sigma}_{n+1}^{T}\mathbf{M}\boldsymbol{\sigma}_{n+1} - \omega_{n+1}^{2}\sigma_{Y}^{2}\left(\bar{\varepsilon}_{n+1}^{p}\right) = 0 \\ \omega_{n+1} - \omega_{n} + \dfrac{\Delta\gamma}{\omega_{n+1}}\left(\dfrac{-Y_{n+1}}{r}\right)^{s} = 0 \end{cases} \tag{12}$$

3. EXPERIMENTAL EXAMPLE

The applicability of the current coupled damage model implementation is illustrated by means of an experimental deep drawing failure case of a cross-shaped sheet metal component [6]. Using an aluminium alloy 5182, failure occurs as shown in Figure 1.

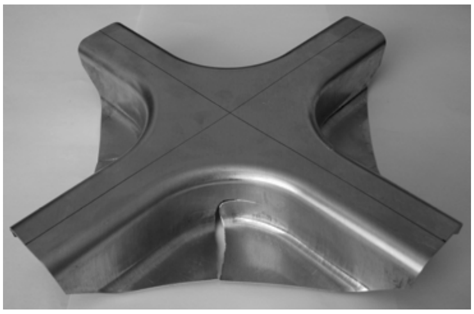

Figure 1. Cross-shaped component with breakage.

3.1 Numerical modelling

Only one quarter of the domain was considered in the simulation and appropriate symmetric conditions have been applied. Blank was modelled with a total of 1186 elements using a double layer of reduced integration solid elements. Tool surfaces were considered fully rigid and discretization was performed using three-noded rigid elements. Concerning material modelling, the sheet material has been treated as an elasto-plastic material with normal anisotropy governed by the Hill's 48 yield criterion [4] and with isotropic hardening described by Swift Law. The main material properties are presented in table 1.

Table 1. Material Properties of AA 5182-O.

Young Modulus [GPa]	69
Poisson Coefficient	0.3
Initial Yield Stress [MPa]	143
Yield Stress [MPa]	$596.123\left(0.001+\bar{\varepsilon}\right)^{0.31}$
R-values	0.67; 0.66; 0.59
Damage exponent	1.0
Damage denominator	1.25 [MPa]

3.2 Results and discussion

The developed damage model was able to predict failure in the same location as in the experimental setting. The maximum value of damage is attained near the cross centre, Figure 2, where high strain localization is reached experimentally, Figure 3.

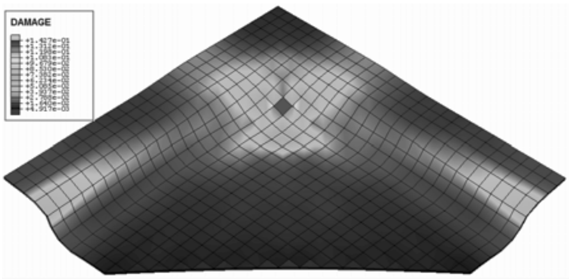

Figure 2. Damage variable contour.

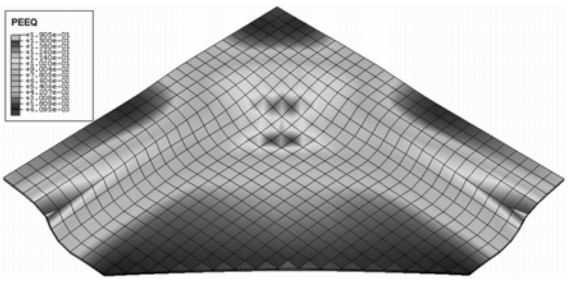

Figure 3. Equivalent plastic strain contour.

It is interesting to note that during stamping, when comparing evolution of damage variable and evolution of equivalent plastic strain we may observe that damage variable grows exponentially when breakage is to occur, while equivalent plastic strain still keeps a constant growth. This exponential evolution is caused by the progressive plastic softening of the material during deep drawing, which reflects the internal degradation on the material response and the fact that $\dot{\varepsilon}^p << \dot{D}$, near the failure site.

4. CONCLUSIONS

A ductile damage model, based on Lemaitre's work [3,5], coupled with Hill's orthotropic plasticity criterion for the prediction of damage in sheet metal forming processes was presented. The model couples, at the constitutive level, material degradation and plastic deformation, within a Continuous Damage Mechanics framework. The resulting constitutive equations were implemented in the Abaqus/Explicit code. To assess the applicability of the developed model, an experimental failure case in deep drawing was utilised. The obtained numerical results illustrate the potential of the implemented model, as it was able to capture the damage evolution and to predict the location of material failure in accordance with the experimental results.

The use of more complex damage models, namely those based on vector or tensor definitions of the damage and a non-local gradient damage approach, will be investigated in the future work .

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